Nanometer scale wire structures fabricated by diffusion-induced selective disordering of a GaAs(AlGaAs) quantum well

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A shallow zinc diffusion technique is used to selectively disorder a GaAs quantum well creating nanometer scale wire structures. Spectrally resolved cathodoluminescence images of the structures are presented as well as local spectra of cathodoluminescence emission from the structures. Blue shifting of the luminescence from the wire structures is observed.

Certain material growth and fabrication technologies now allow the control of composition and structure in materials at the nanometer size scale. Control of composition on this scale epitaxially in one dimension (e.g., quantum well and superlattice material) has been available commercially for several years and is now yielding a number of devices that exhibit novel properties which can be precisely controlled during device fabrication. These include ultralow threshold quantum well semiconductor lasers, resonant tunneling devices, and high electron mobility structures. In addition, this capability has led to important basic discoveries such as the quantum Hall effect and the fractional quantum Hall effect. Control of the other two dimensions of the material on this scale has been and remains a very challenging area of device research. Such lateral control permits fabrication of so-called quantum wire and quantum dot structures, the one- and zero-dimensional analogs of the conventional two-dimensional quantum well. One approach to this control is to employ beam writing systems to lithographically pattern material and then apply some form of processing to transfer the pattern into the material. To date, processing techniques investigated include etching of the material[1,2] or ion implantation.[3] In the former approach, however, a free-semiconductor interface is created which must be passivated to improve radiative efficiency for example, and in the latter approach, a damage field is created by the ion implantation process.

In this letter, we report on the use of a shallow zinc diffusion technique to selectively disorder a GaAs quantum well thereby creating a lateral band-gap modulation. A silicon lift-off technique is used to define a striped diffusion mask with silicon stripes as narrow as 1600 Å. Cathodoluminescence (CL) spectra of the sample confirm complete disordering of the quantum well in the unmasked regions, while areas within the striped mask region show the emergence of a luminescence peak which is blue shifted with respect to the quantum well peak. The blue shift increases as the mask width is decreased. The spectrum in large masked areas (40 μm square) is found to be unaffected except for a reduction in luminescence efficiency.

The sample was grown by molecular beam epitaxy in a Riber 2300 R&D system. The layers were grown in the following order: a 1 μm GaAs buffer layer, a 500 Å AlAs blocking layer, a 1.5 μm $Al_{0.3}Ga_{0.7}As$ buffer layer, a superlattice buffer layer consisting of three 70 Å GaAs layers separated by 70 Å $Al_{0.3}Ga_{0.7}As$ layers, a 0.23 μm $Al_{0.3}Ga_{0.7}As$ layer, a 100 Å GaAs quantum well, and a 500 Å $Al_{0.17}Ga_{0.83}As$ cap layer. All layers were undoped. A diffusion mask was created on this sample using a combination of electron beam lithography and a silicon lift-off technique. The sample was spin coated with a 3% polymethylmethacrylate (PMMA) solution at 3500 rpm. Electron beam lithography was performed in a modified Cambridge Instruments S-240 scanning electron microscope (SEM). Narrow lines, 4.5 μm long, ranging from 1600 Å to 5000 Å in width, were written in array patterns and as isolated lines. In addition, a region 40 μm square was exposed uniformly to provide a broad mask for comparison. After development, the sample was placed in an electron beam evaporator and a 500 Å layer of silicon was deposited. Lift-off was done with dichloromethane. Figure 1 shows a typical array of silicon stripes on the surface of the sample.

Silicon has been shown to be an excellent mask material for zinc diffusion.[4] Following the standard procedure for zinc diffusion in GaAs, the sample was sealed in an evacuated, fused quartz ampoule with solid zinc arsenide as the diffusion source. Zinc diffusion in GaAs-AlGaAs heterostructures is known to enhance the interdiffusion of Ga and Al, disordering regions with a high concentration of zinc, while leaving other areas unaffected.[5]

Investigation of the effects of the zinc diffusion on the band structure of the sample was performed using CL. In

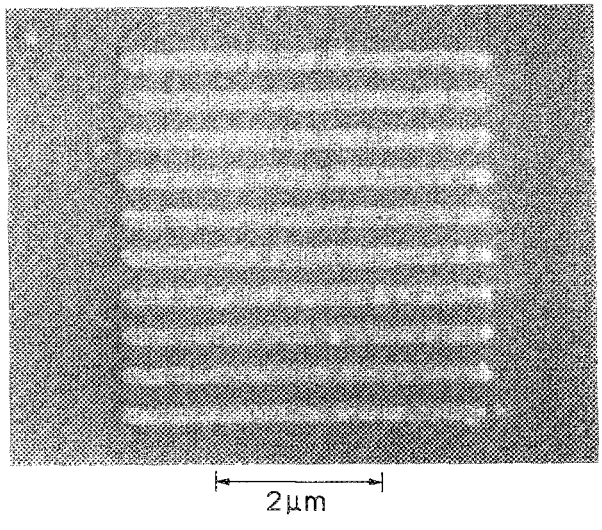

FIG. 1. Scanning electron micrograph of a typical diffusion mask array of silicon stripes.

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this technique sample luminescence generated by an incident electron beam is collected and analyzed. By performing CL in a SEM, one can choose a small, specific region and obtain a very local spectrum.[6] Alternatively, a specific wavelength can be selected and the beam rastered across the sample to generate a spectrally resolved image. In either case, the spatial resolution is determined by the carrier diffusion length and the size of the electron beam interaction volume with the sample.

Measurements were performed to investigate the degree of lateral diffusion under a silicon mask. For these studies, diffusions over much longer periods of time were performed to achieve much deeper diffusion fronts. After diffusion, CL measurements confirmed that the quantum well was intact under the masked areas and completely disordered in unmasked areas. The disordering was observed to extend approximately 1 μm under the mask, indicating the presence of lateral diffusion. Sample cross sectioning and staining, followed by examination in an optical microscope, confirmed this observation. The diffusion front was seen to have moved laterally under the mask a distance roughly equal to that in the downward direction.

A series of diffusion calibrations established that a 1 h diffusion at 535 °C was sufficient to disorder the quantum well, but not so deep as to disorder the superlattice. This placed the disorder front at a depth between 600 and 2800 Å. For these calibration measurements the CL system was used to measure the disappearance of the quantum well emission peak as well as the spatial uniformity of the diffusion process. CL spectra from uniformly masked and unmasked areas of the sample (after the 535 °C diffusion) are presented in Fig. 2. The spectra were taken under excitation by 20 kV electrons at a current of approximately 200 nA at a temperature of 77 K. Two peaks appear in the spectrum from the uniformly masked region. The smaller peak at 789 nm is identified as the quantum well and the peak at 772 nm is the superlattice. The relative intensity of these peaks is controlled by the accelerating voltage of the excitation beam and is not an indication of the relative quality of the layers. The spectrum from the uniformly masked region was found to be identical in form to a sample spectrum taken prior to the diffusion. This shows that the broad area mask successfully protected the quantum well during the diffusion and that all changes noted below can be attributed to the diffusion process (i.e., not to other effects such as temperature cycling).

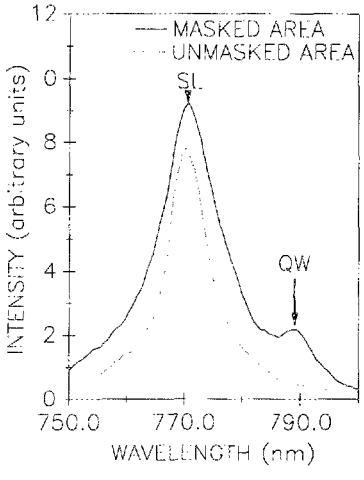

FIG. 2. Cathodoluminescence spectra of a uniformly masked region and an unmasked region. The sample temperature is 77 K.

On the same sample was a series of silicon wire masks. Figure 3 shows both the secondary electron and CL images of a region containing seven arrays of wires and several single wires. The left half of the figure shows the conventional SEM micrograph of the silicon wires. The elements of the arrays range from 1600 Å wide (lower right array) to 3700 Å wide (upper left array). The single lower wire is 5000 Å wide. The right half of the figure shows the same structures except now viewed using spectrally resolved CL with the wavelength adjusted to 780 nm. The wavelength of 780 nm was found to give the greatest contrast between the wires and the background. Due to carrier diffusion, CL is not able to resolve the individual elements in each array, but the single 5000 Å element is resolved. All arrays tested generated CL images similar to those shown in Fig. 3.

Cathodoluminescence spectra of individual arrays were taken by placing the electron beam at the center of an array. Spectra of arrays with mask stripe widths of 3700 Å (broad wires) and 3100 Å (narrow wires) are shown in Fig. 4. The spectra were taken under excitation by 10 kV electrons at a current of approximately 20 nA at a temperature of 12 K. The emission spectra from the broad and narrow wire array structures are intermediate to both the superlattice peak and the quantum well peak. (The quantum well and superlattice peak positions shown in Fig. 4 are as measured at 12 K, not at 77 K as in Fig. 2). Since the superlattice emission peak is unshifted by the diffusion, we conclude that the quantum well peak is blue shifting to produce the peaks seen in the wire spectra. Shifts of 21 and 30 meV are seen in the broad and narrow wire arrays as compared to the quantum well. Spectra from masked areas containing narrower stripes exhibited features that were merging with those of the back-

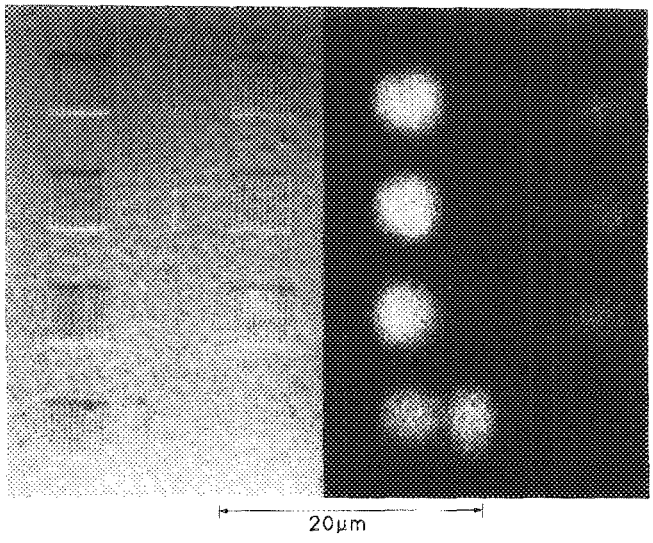

FIG. 3. Secondary electron and cathodoluminescence images of several arrays of wires and an isolated wire. The left half shows the silicon mask as a conventional SEM micrograph. The width of the silicon stripes in the arrays varies from 3700 Å (upper left array) to 1600 Å (lower right array). The right half shows the spectrally resolved cathodoluminescence image of the same region at a wavelength of 780 nm. The sample temperature is 77 K.

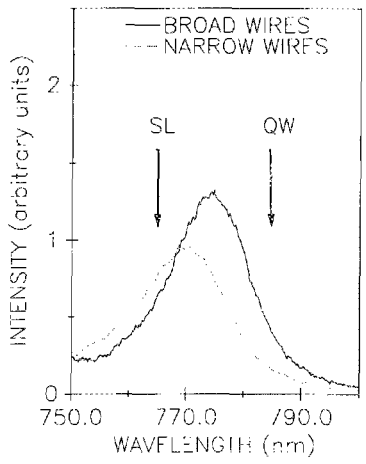

FIG. 4. Cathodoluminescence spectra of a 3700-Å-wide wire masked region, and a 3100-Å-wide wire masked region. The sample temperature is 12 K. The peak positions of the quantum well and superlattice at this temperature are indicated by the arrows.

ground spectra. One mechanism for the observed blue shift on the array spectra is increasing confinement by the lateral diffusion induced potential. It is expected that the width of the confinement potential would decrease with decreasing mask width, and furthermore, that the actual potential width will be narrower than the mask width due to lateral zinc diffusion. Although the blue shift increases with decreasing mask width, it is not possible to attribute this to a quantum size effect with certainty. Another possible mechanism for producing the observed shifts is the introduction of a small amount, approximately 2%, of aluminum into the quantum well. We are continuing to investigate the origin of the shifts.

In conclusion, we have employed a zinc diffusion technique to create a lateral nanometer-scale band-gap variation in a GaAs quantum well. The diffusion process utilized a mask of silicon stripes as narrow as 1600 Å to induce selective disordering of the quantum well. Spectrally resolved cathodoluminescence micrographs were presented showing selectively disordered patches of wire structures. Local cathodoluminescence spectrum indicate that the emission spectrum from the wire structures is blue shifted. The origin of this blue shift is under further investigation.

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